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14. ABSTRACT
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This study is accompanied by a FEM-based micromechanical addressing of the composite. A set of fibre arrangements is considered so as to match reported laminate properties, looking for a consistent layout to include the Z-pins effect.
These treatments fall within linear elastic behaviour, and are essential to a sound study of the upcoming inelastic regime.

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PREPARED BY: JAIME AGUILAR M, MAURICIO BARRERA, GUILLERMO JARAMILLO P.
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SUMMARY

The Epoxy Lamina (EL) concept is introduced to explain overall stiffness reduction in Z-pin reinforced composite laminates, as reported by Zhang et al[1], for a typical 2%-vol fibre content. The concept is applied to a quasi-isotropic laminate, whereby both the softening and strengthening effects are separated out and quantified, based upon experimental data[1].
This study is accompanied by a FEM-based micromechanical addressing of the composite. A set of fibre arrangements is considered so as to match reported laminate properties, looking for a consistent layout to include the Z-pins effect.
These treatments fall within linear elastic behaviour, and are essential to a sound study of the upcoming inelastic regime.

INTRODUCTION

Material fracture/collapse is the last scenario in its behaviour. A systematic treatment requires a thorough understanding of preceding regimes, i.e. elastic and inelastic. The former was addressed during the first year of the ongoing project, intending to establish what the role is that Z-pins may play. Their effect upon the elastic constants could later be linked to an inelastic onset criterion. This way the present study constitutes a necessary foundation to the modelling of the material's inelastic behaviour.
Also within the realms of linear elasticity, a FEM –based micromechanical study of the laminated composite, reported in an accompanying document, ran parallel to the theoretical one, which is exposed first.

METHODS

Lamination Theory and axial elastic modulus prediction

Kirchoff's lamination theory was used to study the mechanical behaviour of laminated composites and the Z-pin's effect on elastic constants. This is introduced by several authors as an engineering design too, with these materials. In what follows the proofs to solid

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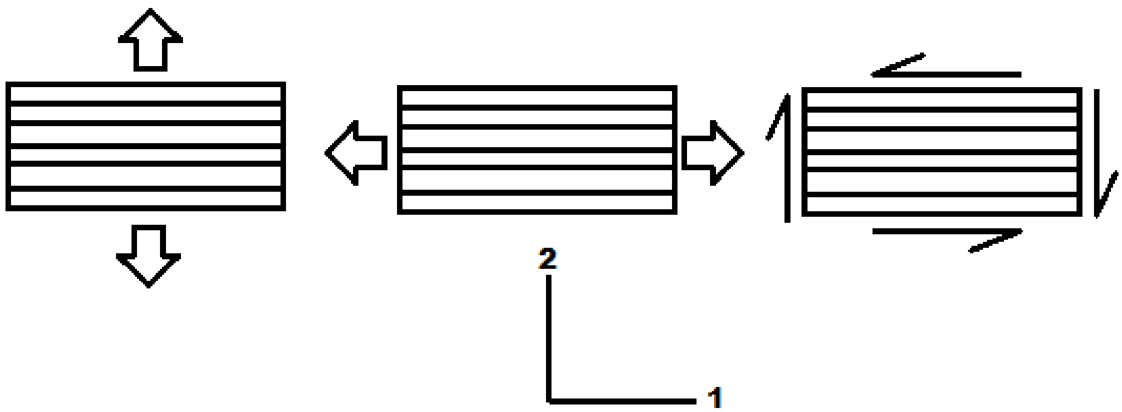
[1] Zhang et al, "*Stiffness and stresses in Z-fibre reinforced composite laminates*", Composites A, 33 (2002), 1653-1664.

mechanics related statements can be found in the references indicated at the bottom of the page.
Fundamental aspects of lamination theory that lead to results linkable to Z-pin effects come in connection to the relationship between individual lamina and composite laminate's elastic properties.
That said each lamina is taken as an orthotropic element subject to plane stress condition. In this case the constitutive matrix is the same to that for a transversely isotropic material[2].
There are four independent elastic engineering constants to an orthotropic material under plane stress. These differ from constitutive matrix entries, resulting from the simple application of material symmetry rules[3]. The specimen-external load line up for elastic engineering constants measurement is set out below:



Coordinate axes 1 and 2 are aligned to material's symmetry, as given by the reinforcing fibre orientation. These axes are called "material axes", and they may be arbitrarily placed with respect to an inertial frame, the latter being fixed to the load's application system.
From left to right in the figure above, the following properties are obtained: transverse elastic modulus E_2; axial elastic modulus E_1 and Poisson's ratio ν_{12}; elastic shear modulus G_{12}. The ratio ν_{21} is obtained from (E_1, E_2, ν_{12})[4].
Lamina's engineering constants are related to strain-stress (compliance) matrix entries as shown below:

$$\{\varepsilon\}_{12} = [S]_{12}\{\sigma\}_{12};$$

$$S_{11} = \frac{1}{E_1} \quad S_{12} = -\frac{\nu_{21}}{E_2}$$

$$S_{22} = \frac{1}{E_2} \quad S_{66} = \frac{1}{G_{12}}$$

The stress-strain constitutive matrix is the stiffness matrix **Q**, related to the compliance matrix **S**:

$$\{\sigma\}_{12} = [Q]_{12}\{\varepsilon\}_{12};$$

$$Q_{ij} = f_{ij}(S_{ij})$$

[2] Herakovich: "*Mechanics of Fibrous Composites*", Chapter 4.
[3] Herakovich: "*Mechanics of Fibrous Composites*", Chapter 3.
[4] Gibson: "*Principles of Composite Material Mechanics*", Chapter 3.

Hence it is possible to set up **Q** matrix from each lamina's engineering elastic constants. Application of orthogonal transformations produces the global form of the **Q** matrix, that is, suitable to an arbitrary direction for load application:

$$\{Q_{ij}\}_{XY} = \{g_{ij}(Q_{ij})\}_{12}$$

The XY and 12 subscripts refer to global (i.e. load application) and local (i.e. material) frames, respectively. The explicit form of this relationship can be found in composite's engineering design textbooks[5].

$\mathbf{Q}_{XY}$ matrix characterises each lamina within a composite laminate, following Kirchoff's theory. This also states lamina thickness and stacking sequence explicitly, through sub-matrices **A**, **B**, **D**. These make up the loads (N, M) - midplane strains (ε, κ) relationship[6]:

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix}$$

Kirchoff's theory assumes that each lamina's thickness is small enough so that the actual layer of matrix material found between reinforcing fibre layers is negligible.

In the case of symmetric and quasi-isotropic laminates, the axial elastic modulus can be predicted by the expression:

$$E_{theoretical} = \frac{1}{a_{11}^*}$$

The quantity in the denominator is the first entry (1° row, 1° column) of matrix $T\mathbf{A}^{-1}$, where T is the laminate's thickness. Experimental results for T300/5208 composite indicate that Kirchoff's lamination theory is satisfactory at estimating laminate's elastic properties[7]. It is observed, however, that the estimated axial elastic modulus is higher than the experimental.

Next on there it is a computer implementation of the method just introduced. It uses Scilab® programming language, and the Young modulus is calculated as final output.

```
//This script analyses symmetric, cross ply laminates
//based on Kirchoff's lamination theory (composite
//plate). Ref: Herakovich's
//Part A: engineering constant values (T300/5208)
E1=132;//axial modulus, Gpa
E2=10.8;//transverse modulus, Gpa
u12=0.24;//in-plane Poisson's ratio
G12=5.65;//in-plane shear modulus, Gpa
u21=(E2/E1)*u12;
//Part B: compliance matrix's entries, plane stress,
//material frame
S11=1/E1;S12=-u21/E2;S22=1/E2;S66=1/G12;
//Part C.1:Q-matrix's entries (4.13), material frame
Q11=S22/((S11*S22)-(S12^2));
Q22=S11/((S11*S22)-(S12^2));
Q12=-S12/((S11*S22)-(S12^2));
Q66=1/S66;
```

[5] Herakovich: "*Mechanics of Fibrous Composites*", Chapters 4 and 5.

[6] Herakovich: "*Mechanics of Fibrous Composites*", Chapter 5; Gibson: "*Principles of Composite Material Mechanics*", Chapter 7.

[7] Herakovich: "*Mechanics of Fibrous Composites*", Figure 5.11

```
//Part C.2: matrix "data" gathering laminate sequence, laminae
//thicknesses, off axis angle, Zk's needed to set up Qb and A,
//B, D matrices
N=input("Number of laminae...");
data=zeros(N,7);
for i=1:N
  data(i,1)=0.127/1000;//input laminae thickness.
  disp(i,"this is laminae #")
  data(i,2)=input("off axis orientation...");
  data(i,3)=cosd(data(i,2));
  data(i,4)=sind(data(i,2));
end
data(1,[5 6 7])=[data(1,1) data(1,1)^2 data(1,1)^3];
for i=2:N
  data(i,5)=data(i,1)+data(i-1,5);//Zi
  data(i,6)=(data(i,5))^2-(data(i-1,5))^2;
  data(i,7)=(data(i,5))^3-(data(i-1,5))^3;
end
//Part D.1: Qb lab frame (4,34);A,B,D matrices loop starts off
//here
A=zeros(3,3);B=zeros(3,3);D=zeros(3,3);T=0;
for i=1:N
  m=data(i,3);n=data(i,4);
Qb11=Q11*(m^4)+2*(Q12+2*Q66)*(m^2)*(n^2)+Q22*(n^4);
Qb12=(Q11+Q12-(4*Q66))*(m^2)*(n^2)+Q12*((n^4)+(m^4));
Qb22=Q11*(n^4)+2*(Q12+2*Q66)*(m^2)*(n^2)+Q22*(m^4);
Qb16=(Q11-Q12-2*Q66)*(m^3)*n+(Q11-Q12+2*Q66)*(n^3)*m;
Qb26=(Q11-Q12-2*Q66)*(n^3)*m+(Q11-Q12+2*Q66)*(m^3)*n;
Qb66=(Q11+Q22-2*Q12-2*Q66)*(m^2)*(n^2)+Q66*((n^4)+(m^4));
//Part D.2: Stiffness matrix Qb, lab frame
Qb=zeros(3,3);
Qb(1,1)=Qb11;Qb(1,2)=Qb12;Qb(2,2)=Qb22;
Qb(1,3)=Qb16;Qb(2,3)=Qb26;Qb(3,3)=Qb66;
Qbt=Qb';
S=zeros(3,3);
S([2 3],1)=Qbt([2 3],1);
S(3,2)=Qbt(3,2);
Qb=Qb+S;
//Part D.3:assembling A, B, D matrices-laminae stacking
A=A+data(i,1)*Qb;
B=B+(1/2)*data(i,6)*Qb;
D=D+(1/3)*data(i,7)*Qb;
T=T+data(i,1);//laminate thickness
end
//Part E: Laminate engineering constants
a=T*inv(A);
Ex=1/a(1,1);//Laminate's Ex (axial).
```

Epoxy Layer (EL) concept.

From the observation that the estimated elastic modulus is higher than the experimental, it was deemed that this difference is due to a non-negligible thickness of the matrix material

in between reinforcing fibre layers. Therefore, a set of interspersed layers made of matrix material alone could be explicitly declared within Kirchoff's theory, this idea defines the Epoxy Layer (EL) concept. The matrix material thickness that makes Young's modulus prediction match the experimental one becomes an additional feature of the composite. This thickness can be associated to an excess of matrix material at the time of composite lay-up.
Within the Young's modulus estimation algorithm, EL's thickness is an input. Thus, finding this value to a particular case is an iterative process, in principle.
A computer implementation of the EL concept is set out next:

```
clear;
//This script analyses symmetric, cross ply laminates
//based on Kirchoff's lamination theory (composite
//plate). Ref: Herakovich's
//Part A: engineering constant values (T300/5208)
E1=132;//axial modulus, Gpa
E2=10.8;//transverse modulus, Gpa
u12=0.24;//in-plane Poisson's ratio
G12=5.65;//in-plane shear modulus, Gpa
u21=(E2/E1)*u12;
//
E=4.6;//%Epoxy matrix's E
u=0.36;//%Epoxy matrix's u
G=E/(2*(1+u));//%Epoxy matrix's G
//Part B: compliance matrix's entries, plane stress,
//material frame
S11=1/E1;S12=-u21/E2;S22=1/E2;S66=1/G12;
//
S11iso=1/E;S12iso=-u/E;S22iso=1/E;S66iso=1/G;
//Part C.1:Q-matrix's entries, material frame
Q11=S22/((S11*S22)-(S12^2));
Q22=S11/((S11*S22)-(S12^2));
Q12=-S12/((S11*S22)-(S12^2));
Q66=1/S66;
//
Q11iso=S22iso/((S11iso*S22iso)-(S12iso^2));
Q22iso=S11iso/((S11iso*S22iso)-(S12iso^2));
Q12iso=-S12iso/((S11iso*S22iso)-(S12iso^2));
Q66iso=1/S66iso;
//Part C.2: matrix "data" gathering laminate sequence, laminae
//thicknesses, off axis angle, Zk's needed to set up Qb and A,
//B, D matrices
N=input('Number of unidirectional laminae...');
data=zeros((2*N)-1,8);
t=input('input laminae thickness (sugg.0.127/1000)...');//laminae
//thickness.
tepox=input('input epoxy interlayer thickness...');
data(1:2:(2*N)-1,1)=t;
data(2:2:(2*N)-2,1)=tepox;
z0=((2*N-1)*t)/2;//one half laminate thickness
for i=1:2:(2*N)-1//loop for unidirectional laminae
  disp('this is laminae #');disp(i);
```

```
  data(i,2)=input('off axis orientation...');
  data(i,3)=cosd(data(i,2));
  data(i,4)=sind(data(i,2));
end
data(1,[5 6 7 8])=[(z0-data(1,1)) (data(1,5)-z0) (data(1,5)^2-
z0^2) (data(1,5)^3-z0^3)];//[(z1) (z1-z0) (z1^2-z0^2) (z1^3-z0^3)]
for i=2:(2*N)-1//Zi's for every single layer, uni and iso
  data(i,5)=data(i-1,5)-data(i,1);//   Zi
  data(i,6)=data(i,5)-data(i-1,5);//Zi - Zi-1
  data(i,7)=(data(i,5))^2-(data(i-1,5))^2;//Zi^2 - Zi-1^2
  data(i,8)=(data(i,5))^3-(data(i-1,5))^3;//Zi^3 - Zi-1^3
end
//Part D.1: Qb lab frame;A,B,D matrices loop starts off //here
A=zeros(3,3);B=zeros(3,3);D=zeros(3,3);T=0;
k=1;
for i=1:(2*N)-1
  if (i-k)==0
m=data(i,3);n=data(i,4);
Qb11=Q11*(m^4)+2*(Q12+2*Q66)*(m^2)*(n^2)+Q22*(n^4);
Qb12=(Q11+Q12-(4*Q66))*(m^2)*(n^2)+Q12*((n^4)+(m^4));
Qb22=Q11*(n^4)+2*(Q12+2*Q66)*(m^2)*(n^2)+Q22*(m^4);
Qb16=(Q11-Q12-2*Q66)*(m^3)*n+(Q11-Q12+2*Q66)*(n^3)*m;
Qb26=(Q11-Q12-2*Q66)*(n^3)*m+(Q11-Q12+2*Q66)*(m^3)*n;
Qb66=(Q11+Q22-2*Q12-2*Q66)*(m^2)*(n^2)+Q66*((n^4)+(m^4));
//Part D.2: Stiffness matrix Qb, lab frame
Qb=zeros(3,3);
Qb(1,1)=Qb11;Qb(1,2)=Qb12;Qb(2,2)=Qb22;
Qb(1,3)=Qb16;Qb(2,3)=Qb26;Qb(3,3)=Qb66;
Qbt=Qb';
S=zeros(3,3);
S([2 3],1)=Qbt([2 3],1);
S(3,2)=Qbt(3,2);
Qb=Qb+S;
end
if (i-k)~=0
Qb=zeros(3,3);
Qb(1,1)=Q11iso;Qb(1,2)=Q12iso;Qb(2,2)=Q22iso;
Qb(3,3)=Q66iso;Qb(2,1)=Q12iso;
k=i+1;
end
//Part D.3:assembling A, B, D matrices-laminae stacking
A=A+t*Qb;//simplified Zi - Zi-1 = laminae thickness t
B=B+(1/2)*data(i,7)*Qb;
D=D+(1/3)*data(i,8)*Qb;
end
//Part E: Laminate engineering constants
T=(N*t)+((N-1)*tepox);//laminate thickness
a=T*inv(A);
Ex=1/a(1,1);//Laminate's Ex (axial).
```

EL concept application to Z-pin's effect on Young's modulus

Observing composite specimens where unreinforced and Z-pin reinforced regions meet together, there emerges a difference in thickness. The Z-pin zone is noticeably thicker: about 1 mm difference in a ~ 2 cm by ~ 20 cm flat specimen. This could be due to the Z-pin insertion process itself.

In this scenario, two competing factors can be identified: on the one hand, an increase in laminate's thickness, with the same number of reinforcing fibre layers, implies that there has been an increase in matrix material thickness. This produces a stiffness loss to the composite (Kirchoff's theory plus EL concept).

Then again, each matrix material layer is itself crossed by Z-pins. Looking perpendicular to the laminate's plane, these Z-pins constitute a reinforcing phase embedded into the matrix material[8]. This way, Z-pins increase the composite's stiffness.

Zhang et al report that both experimental results and FEM-based micromechanical analyses yield an overall stiffness reduction of 7% to 10%, when considering in-plane Young's modulus.

To explore this situation, the EL concept can be applied in four steps, as follows:

1. Taking an experimental Young's modulus value from a laminate without Z-pins, its thickness, lamina stacking sequence and lamina's engineering elastic constants, the second Scilab® code can be used to find the EL thickness, so that the predicted Young's modulus matches the available, experimental one.
2. Using the thicknesses for Z-pin reinforced laminate, un-reinforced laminate and EL just found in the previous step, the EL thickness *to the Z-pin reinforced region* is computed.
3. Using the last EL thickness, the second Scilab® code is employed once again; this time, though, a new Young's modulus estimate would be produced. On the other hand, an experimental value of this modulus for the Z-pin reinforced composite must be available.
4. It is expected that this experimental value must be higher than the predicted one in step 3, for this prediction considers only the loss of stiffness due to the EL. More specifically, experimental Young's modulus would be F times the predicted one, where F>1, and:

$$F = (E_{experimental}/E_{predicted})_{Z\text{-}pin}.$$

This definition could then be identified as the stiffening factor due to Z-pins. On the same grounds, EL thickness is identified as a softening factor, albeit embedded into modulus prediction calculations.

RESULTS

Step 1

Laminate without Z-pins, data:

Stacking sequence: $[45,0,-45,90]_s$.

Laminate thickness: 4mm

Experimental Young's modulus: 53.34 Gpa.

[8] Zhang et al, "*Stiffness and stresses in Z-fibre reinforced composite laminates*", Composites A, 33 (2002), 1653-1664.

Lamina properties: (AS4/3501-6; (E_1, E_2, ν_{12}, G_{12})): 136.4 GPa, 8.90 GPa, 0.25, 5.95 GPa.
Matrix properties (epoxy resin; (E, ν)): 4.44 GPa, 0.34.

Results:
Estimated Young's modulus, without EL: 57.69 GPa.
Proposed EL thickness: 0.04 mm
Reinforcing layer thickness (altogether): 0.46 mm
Estimated Young's modulus with proposed EL: 53.61 GPa.

Step 2
Z-pin reinforced laminate, properties:
Thickness: 5 mm
Reinforcing layer thickness (altogether): 0.46 mm

Results:
EL thickness: 0.165 mm

Step 3
EL thickness: 0.165 mm

Results:
Estimated Young's modulus: 43.91 GPa.
Experimental Young's modulus, Z-pin reinforced laminate: [49.51 52.35] GPa

Step 4
$E_{experimental}$: [49.51 52.35] GPa
$E_{predicted}$: 43.91 GPa

Results:
F factor: [(49.51/43.91) (52.35/43.91)] = [1.13 1.19]

DISCUSSION

The results confirm the expected EL concept application outcome, at least within the limits of employed data. Thus, the EL concept can separate out stiffness increase and loss contributions due to Z-pins. However, one assumption in the process is that Z-pins have no reinforcing effect onto the fibre layer itself. Addressing this situation certainly demands a micromechanical approach. Nevertheless, it shall first be tested against available data; hence, the micromechanical analysis of a laminate without Z-pins would come as a safe, first step in this regards.

CONCLUSION

The Epoxy Layer (EL) concept was introduced and elaborated on to explain stiffness reduction in Z-pin reinforced laminates, according to selected literature reports. To this end it was considered the in-plane Young's modulus, both experimental and as predicted by turning to Kirchoff's lamination theory.

A four-step methodology for EL concept application was also proposed and tested. A separation of the Z-pin stiffening effect emerges as the main outcome.

Consideration of Z-pin effect on fibre layer's elastic properties was deemed more appropriate for a micromechanical study. This should start by an analysis of the no Z-pin situation first, and is reported in detail in the accompanying document.

MICROMECHANICAL MODELING APPROACH TO CHARACTERIZE CARBON FIBER MATERIAL PROPERTIES.

Developed by: Guillermo Andrés Jaramillo Pizarro.

This report shows a comparison developed through simulation of test specimens of micromechanics in order to explore ply behavior, against the values given by the software NDSANDS (a module of the software named ASCA), working with different geometric microstructural proposals. The goal with this approach is to develop a methodology and a tool for material characterization of the z pinned zone and its mechanical response before a delamination failure.

The main limitation of micromechanical modeling is the lack of available detailed information about the material properties of each one of the volume fractions which compose each ply of the whole laminate material. This approach is based on the seek for simple and feasible acquirable input data to develop micromechanical simulations which could bring reliable data output for material characterization to some kinds of failures. The first one of them in priority is delamination.

However, in the pursuit of this objective, a comparison between the micromechanical modeling approach and data coming from experimental tests, given by the NDSANDS database) must be done. The micromechanical modeling will be done in two types of geometrical fiber distribution, often called hexagonal cell and square cell and they are illustrated in figure1, [1]. The volume fraction of each specie is obtained from NDSANDS database. Further volume fractions of the actual test specimens will be obtained from optical microscopy of current specimens.

Figure 1.Geometrical fiber distribution in micromechanical models. Blue regions are fibers and violet regions are matrix.

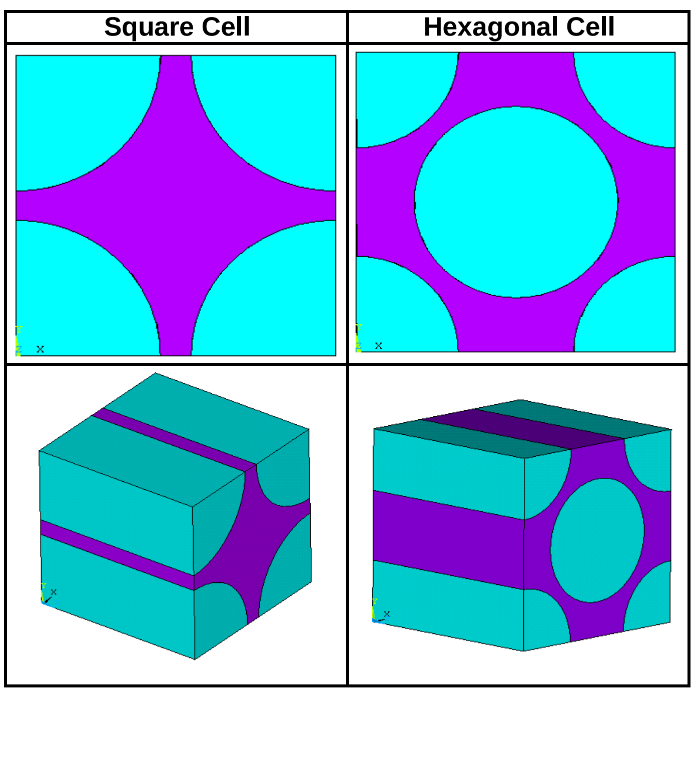


Table 1 shows input data for micromechanical modeling, results and comparison with data given by NDSANDS database for ASC(4)/E828 composite material.

Table 1. Input data and Results of micromechanics models

Model Input Data	Models data with orthotropic fiber properties		Models data with isotropic fiber properties	
Matrix volume fraction	0.360	0.280	0.360	0.280
Fiber volume fraction	0.640	0.720	0.640	0.720
Fiber filament radius (micrometers)	3.500	3.500	3.500	3.500
Fiber orthotropic material data				
Fiber elasticity modulus at z direction in (TPa)	0.235	0.235	N.A.	N.A.
Fiber elasticity modulus at y direction (TPa)	0.014	0.014	N.A.	N.A.
Fiber elasticity modulus at x direction (TPa)	0.014	0.014	N.A.	N.A.
Poisson ratio at xy plane	0.200	0.200	N.A.	N.A.
Poisson ratio at zx plane	0.100	0.100	N.A.	N.A.
Poisson ratio at zy plane	0.100	0.100	N.A.	N.A.
Shear modulus for all directions (TPa)	0.028	0.028	N.A.	N.A.
Fiber isotropic data				
Fiber elasticity modulus (TPa)	N.A.	N.A.	0.235	0.235
Fiber Poisson ratio	N.A.	N.A.	0.200	0.200
Matrix isotropic data				
Matrix elasticity modulus in (TPa)	0.0029	0.0029	0.0029	0.0029
Matrix Poisson ratio	0.350	0.350	0.350	0.350
Hexagonal cell model proposal				
cross section length in micrometers	10.966	10.339	10.966	10.339
model length at z direction in micrometers	10.966	10.339	10.966	10.339
elongation in z direction (micrometers)	0.015	0.015	0.013	0.013
deformation at z direction	0.00137	0.00145	0.00119	0.00126
Hexagonal cell model results				
fiber mean stress in TPa	0.000420	0.000470	0.000320	0.000330
matrix mean stress in TPa	0.000020	0.000017	0.000008	0.000009
material mean stress	0.000276	0.000343	0.000208	0.000240
whole material elasticity modulus at z direction in TPa	0.201784	0.236536	0.175255	0.190975
whole material elasticity modulus at z direction in GPa	202	237	175	191
Error (in comparison with NDSANDS - value 151GPa)	**34%**	**57%**	**16%**	**26%**
Square cell model proposal				
cross section length in micrometers	7.754	7.311	7.754	7.311
model length at z direction in micrometers	7.754	7.311	7.754	7.311
elongation in z direction (micrometers)	0.015	0.015	0.015	0.015
deformation at z direction	0.002	0.002	0.002	0.002
Square cell model results				
fiber mean stress in TPa	0.000600	0.000690	0.000440	0.000490
matrix mean stress in TPa	0.000028	0.000030	0.000045	0.000013
material mean stress in Tpa	0.000394	0.000505	0.000298	0.000356
whole material elasticity modulus at z direction in TPa	0.203726	0.246234	0.153952	0.173729
whole material elasticity modulus at z direction in GPa	204	246	154	174
Error (in comparison with NDSANDS - value 151GPa)	**35%**	**63%**	**2%**	**15%**

The micromechanical modeling was developed as shown in table 1, from input data belong to NDSANDS database for ASC(4)/E828 composite material. The geometrical configuration was specified establishing an equal separation in x and y (the cross sectional axis for the micromechanical model) of the fiber in both configurations, hexagonal and

square. The length of the micromechanical body is calculated according to fiber filament radius which is established as 3.5 μm.

Up to now, just the elasticity modulus at z direction, which is the normal direction to cross sectional area, has been compared with the elasticity modulus of the whole ply at the same direction. The best approach is given by an isotropic consideration of the fiber material (in green at table 1), which is not correct. However, when optical microscopy reveals the actual volume fraction this data could be confront again.

The values in red are used for micromechanical modeling which do not match to NDSANDS database values. These values were used because the limitation of the orthotropic material model used, which is another thing to improve in the modeling.

To continue the micromechanical modeling it is necessary to acquire the actual volume fractions, fiber filament radius and material properties data of actual specimens.

Detailed graphical data from results of Micromechanical Finite Element models are presented in the following tables 2-5 and thus correlated with information given by table 1.

Table 2. Hexagonal cell models results with orthotropic material values. Z direction Stress in TPa.

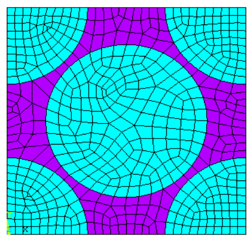
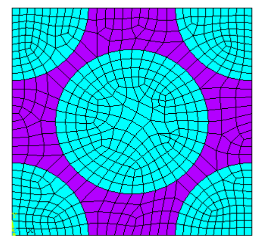
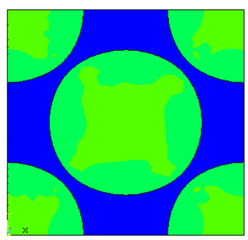
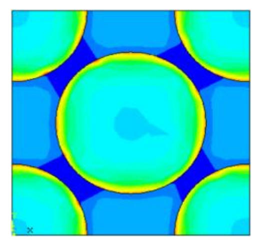
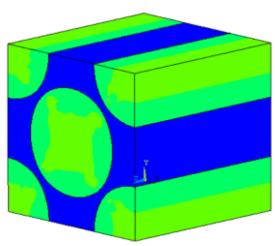
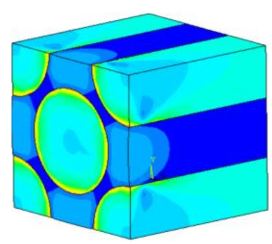
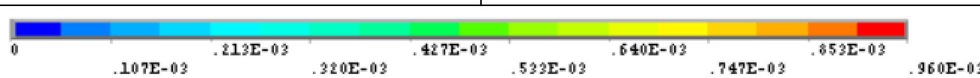
MODELS RESULTS WITH ORTHOTROPIC MATERIAL VALUES Z DIRECTION STRESS (TPa)	
HEXAGONAL CELL PROPOSAL	
MODEL LENGTH 10.34 micrometers	MODEL LENGTH 10.96 micrometers
Fiber volume fraction: 0.72	Fiber volume fraction: 0.64
	
	
	
	

Table 3. Hexagonal cell models results with isotropic material values. Z direction Stress in TPa.

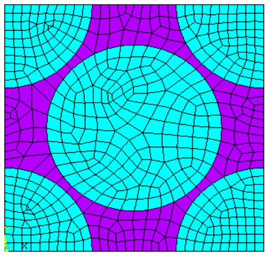
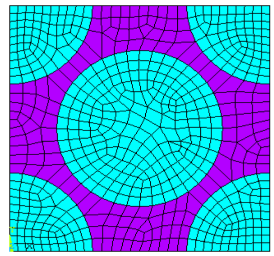
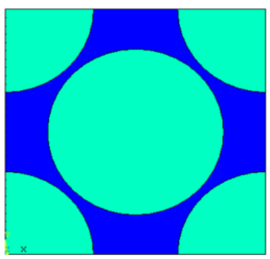
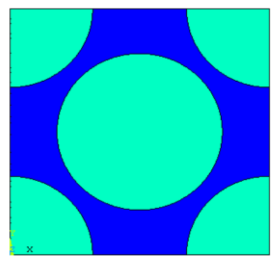
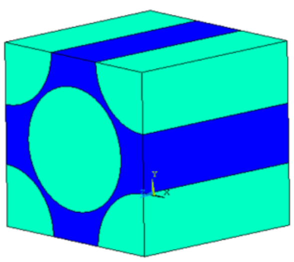
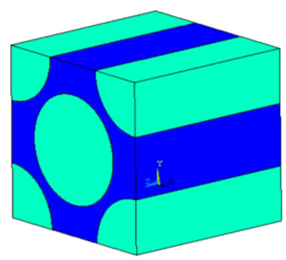
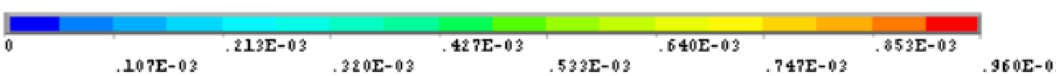
MODELS RESULTS WITH ISOTROPIC MATERIAL VALUES Z DIRECTION STRESS (TPa)	
HEXAGONAL CELL PROPOSAL	
MODEL LENGTH 10.34 micrometers	MODEL LENGTH 10.96 micrometers
Fiber volume fraction: 0.72	Fiber volume fraction: 0.64
	
	
	
	

Table 4. Square cell models results with orthotropic material values. Z direction Stress in TPa.

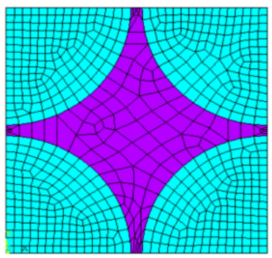
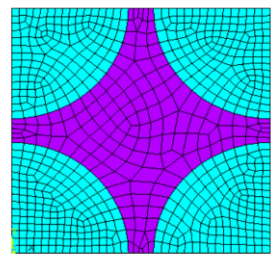
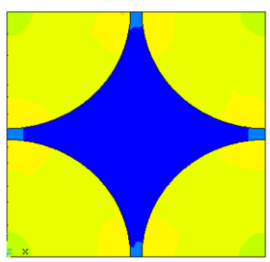
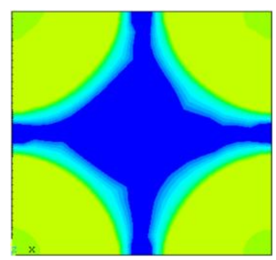
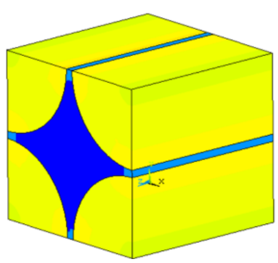
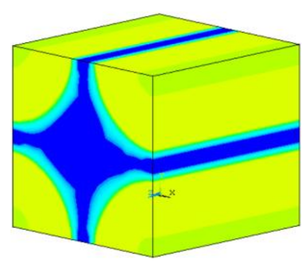
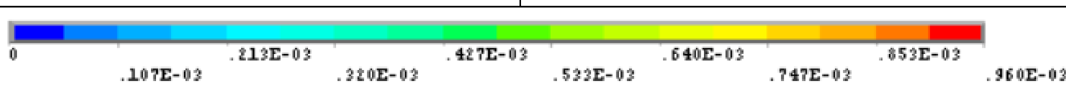
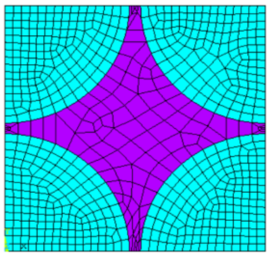
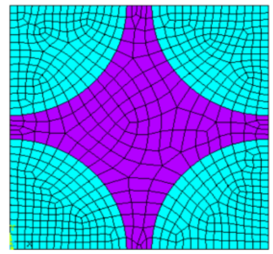
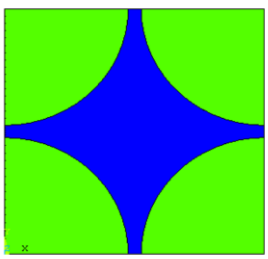
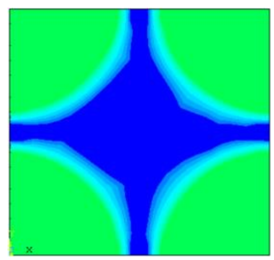
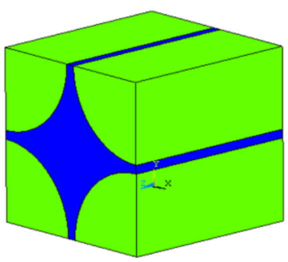
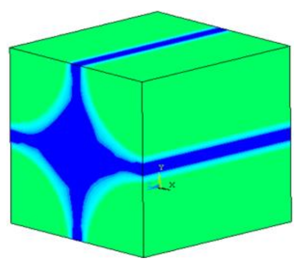
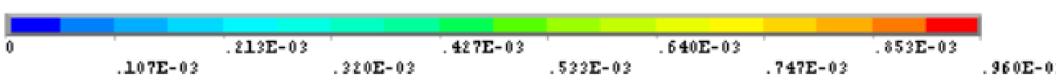
MODELS RESULTS WITH ORTHOTROPIC MATERIAL VALUES Z DIRECTION STRESS (TPa)	
SQUARE CELL PROPOSAL	
MODEL LENGTH: 7.31 micrometers	MODEL LENGTH: 7.75 micrometers
Fiber volume fraction: 0.72	Fiber volume fraction: 0.64
	
	
	
	

Table 5. Square cell models results with isotropic material values. Z direction Stress in TPa.

MODELS RESULTS WITH ISOTROPIC MATERIAL VALUES Z DIRECTION STRESS (TPa)	
SQUARE CELL PROPOSAL	
MODEL LENGTH: 7.31 micrometers	MODEL LENGTH: 7.75 micrometers
Fiber volume fraction: 0.72	Fiber volume fraction: 0.64
	
	
	
	

Results obtained from Square cell models shown in table 5 for the one with a fiber volume fraction of 0.64 are more accurate according to material value data for ASC(4)/E828.

Additionaly to this modeling evaluation, an experimental design is developed and briefly described at the next section .

TEST SPECIMENS AND EXPERIMENTAL DESCRIPTION

An experimental design has been proposed to validate and comparing analytical and numerical results against experimental ones.

Static and Dynamic tests have been scheduled to develop comparisons.

The static tests will be done over four different kinds of specimens. The first one of them corresponds to a specimen without z-pinned zones, obtained from the plate given by professor Som Soni. The test will allow to corroborate and improve the analytical and numerical proposals of material characterization without z pins.The second specimen is entirely constituted by z pins. The static test over this specimen will allow us to determine its mechanical response due to the pins modification over the laminate. The third specimen matches with the ones given by professor Som Soni, including the two zones described above. The objective will be to joint previous material models, comparing with experimental results and tuning the analytical and numerical models. The fourth one static test will be done over a test specimen as shown in figure 2 with three 0.2” holes of diameter, to determine the effect of geometric stress concentration factors in the material.

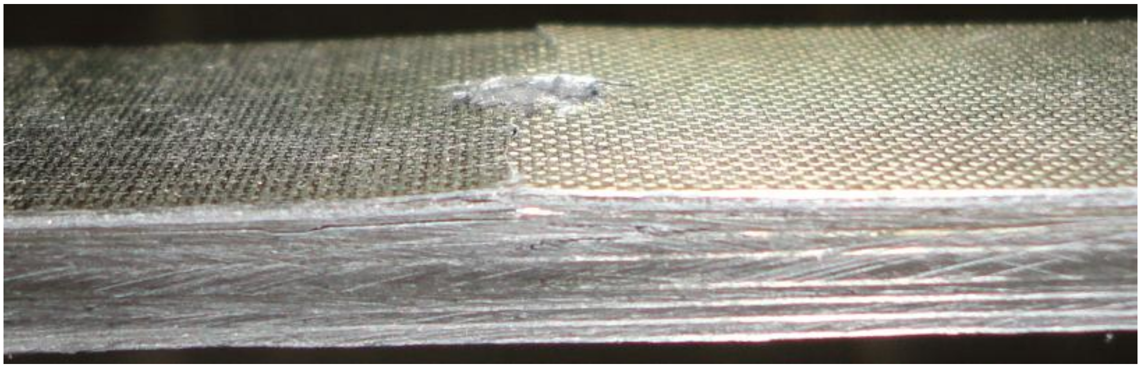
Figure 2.Test specimen with three 0.2” diameter holes to determine the effect of geometric stress concentration factors in the material.

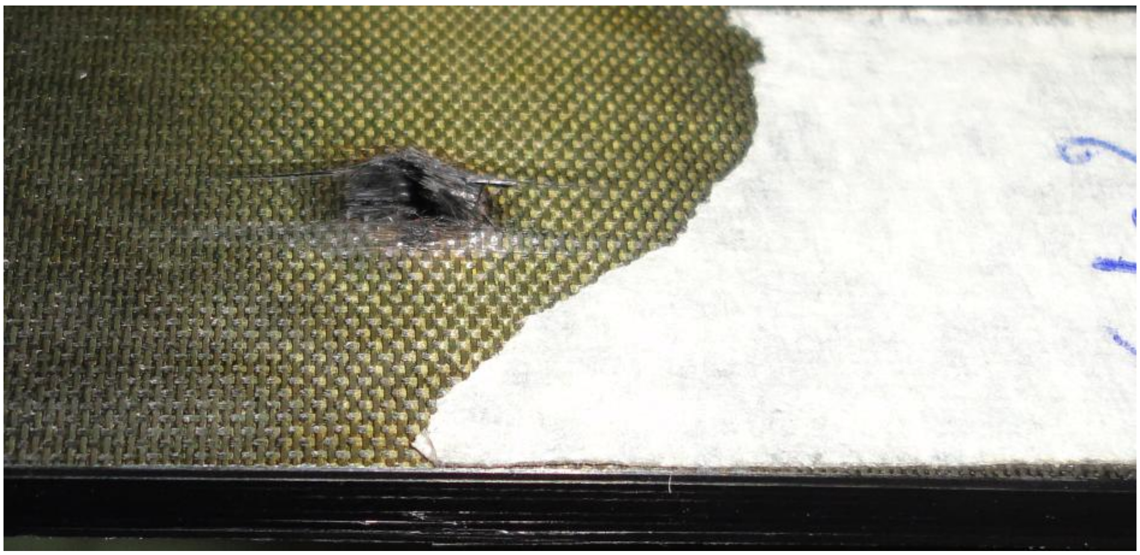
After these tests, dynamical experiments will be done.According to proposed by professor Som Soni dynamic test were earlier established up to 60%, 70% and 80% of the full load, which was 150 ksi. However, the machine employed to develop these tests, allow us to apply loads up to 25000 N. Making the comparison in ksi with the cross sectional area of current specimens delivered by professor Som Soni and cutted by our staff, the equivalent maximum load applicable by our machines is less than 30 ksi, which corresponds to 20% of 150 ksi. We will develop dynamic test with the following parameters, according to our equipment limitations:

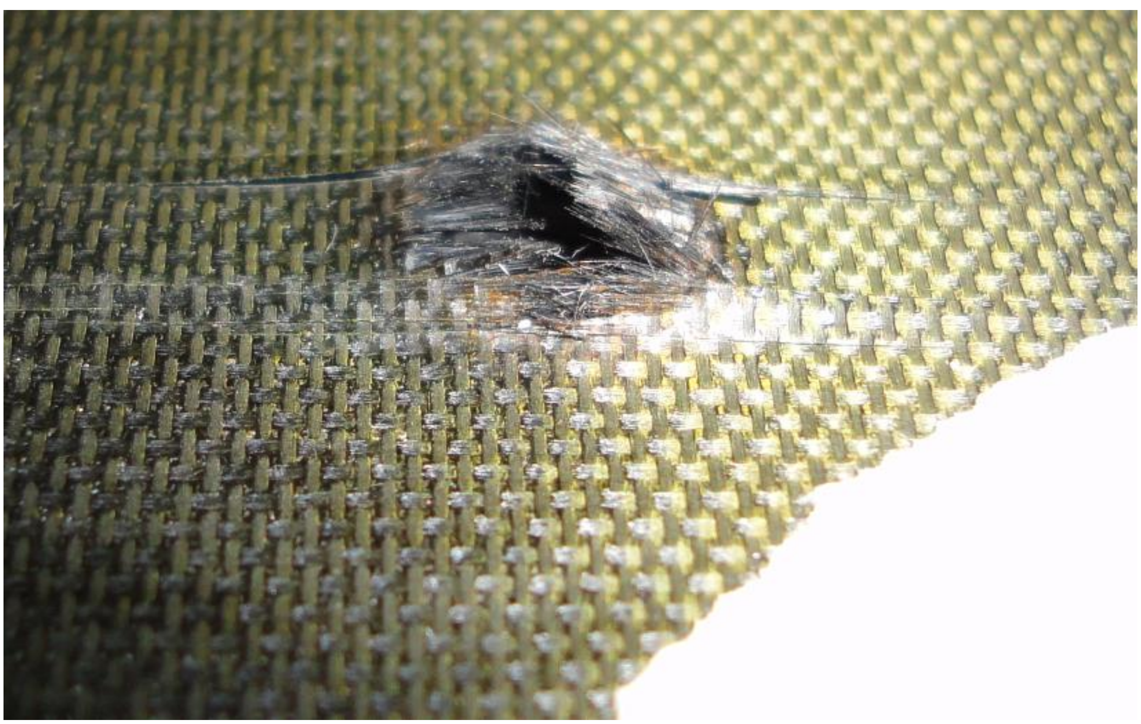
Dynamic test data:
- Frequency (Hz): 5.
- Three different loads (Ksi): 25, 15, 5.
- Minimum load to fatigue tests (Ksi): 2.5.

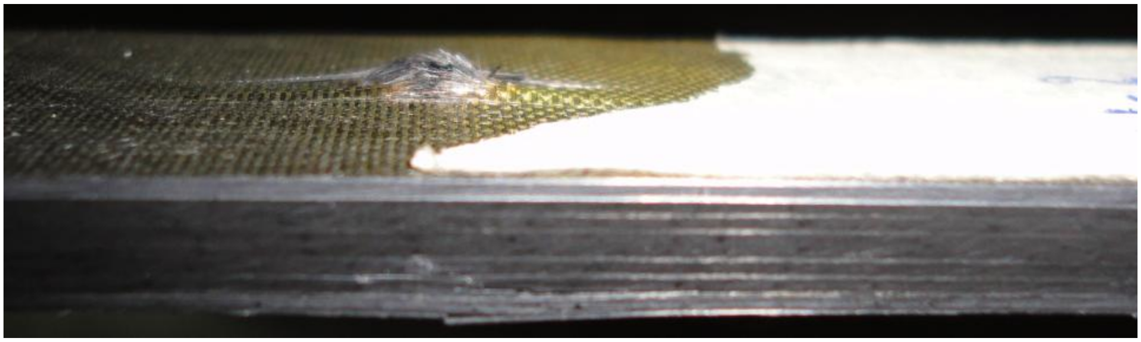
<u>NOTE: Professor Som Soni, The value of 150 ksi is equivalent to 1.035GPa. We have not registered a carbon fiber tensile strength of that magnitude in literature. Please let us know if there is a mistake around this data. Dynamic tests with such high values are not feasible to develop.</u>

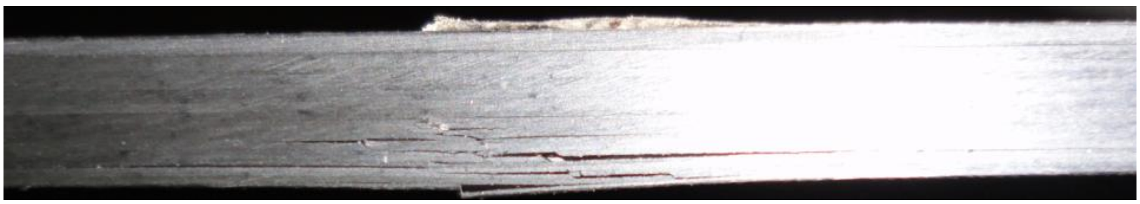
Next figures show a sequence of a test develpoed over a specified specimen.

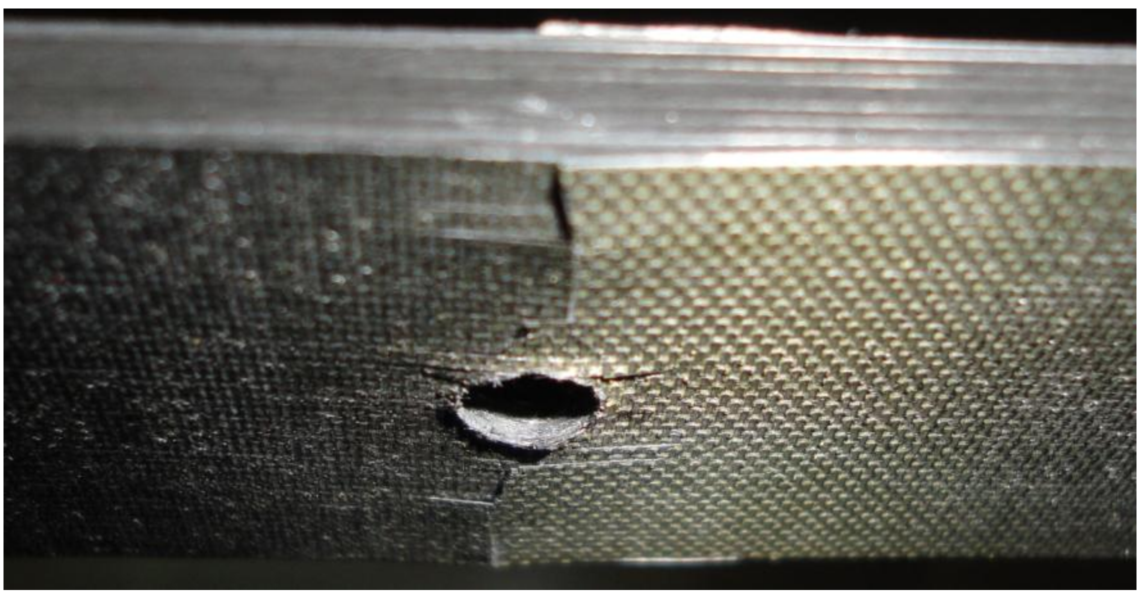












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